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EMC STANDARDS AND REGULATIONS: A BRIEF REVIEW

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EMC Standards and Regulations: A Brief Review

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Important current regulations and standards regarding electromagnetic compatibility (EMC) measurements are reviewed. These regulations and standards have been either enforced by U. S. government agencies such as the Federal Communications Commission and Department of Defense, or incorporated in voluntary industrial practice. The specific methods and configurations of measurement required in some of these standards are assessed from a technical basis to see whether or not they are adequate and appropriate. Technical deficiencies and potential problems, if any, are pointed out together with recommendations of alternative and better methods of measurements. Concurrently, the EMC measurement capability at the National Institute of Standards and Technology is evaluated and appraised for the purpose of planning new metrology activities or programs responsive to the needs of U. S. industry.

Key words: Electric field, electromagnetics, EMC, EMI, emission, magnetic field, measurement methods, requirement, regulation, review, standards, susceptibility.

1. Introduction

Increased electromagnetic (EM) pollution in the environment has caused tremendous concern in the electronics industry and among users. Designers of components and systems want to be sure that their products do not emit excessive, unintentional radiation to interfere with the operation of other systems, nor should these products be susceptible to electromagnetic interference (EMI), which may degrade their performance. Users of electronic products also wish to enjoy intra- and inter-system electromagnetic compatibility (EMC). To realize this ultimate goal of achieving total EMC, recommendations, rules, and requirements (under the general term standards), are issued by regulatory or private organizations as mandatory or voluntary guidelines to the system and component designer.

When recommending standards, the proposers have to consider carefully two important factors, based on sound technical justifications: (1) setting realistic limits on emission and susceptibility, and (2) offering a clear set of measurement procedures with appropriate experimental configurations.

Ideally, the emission and susceptibility limits for a piece of equipment should be specified to represent as closely as possible the EM environment in an anticipated operational condition for that equipment. If a susceptibility limit is over-specified, it will cost the industry and users unnecessarily. For example, if a susceptibility limit to a radiated electric field for one system component is set at 200 V/m while the actual worst case under the operational condition is only 100 V/m, a much better shield would have to be provided to protect this system component for an electric field at 200 V/m even though a less expensive shield may be adequate for protecting the system component against the actual electric field of 100 V/m. On the other hand, a more lenient specification on the susceptibility limit will not achieve the desired total EMC.

To determine the actual emission or susceptibility value for a piece of equipment, measurement procedures and equipment configurations must also be clearly specified within the standard. If they involve any technical deficiency, the measured results may vary substantially or have no physical meaning, depending on the actual condition and environment in which the measurements are performed. When this happens, the EMC objectives will not be fulfilled; the equipment may not function properly in the operational condition. Thus, achieving repeatability of the same essential measurement result, regardless of who is making the measurement, as long as it is done in the same environment and condition, should be the final objective of setting any successful standard. In addition, physical interpretations of the measured results are also important. Do the measured results accurately represent the fact? Are these results accurate only under the assumptions made in the standard? What is the expected accuracy? If one or more assumed conditions are not met, what are then the meanings of the measured data? What changes are expected in the measured result if one parameter in the measurement is changed? These questions can only be answered with adequate understanding of the complicated EM principle.

Unfortunately, users' experience with existing EMC standards indicates that this is not the case. In particular, the results of the standardized tests have been inconsistent, and the measurement data obtained in the laboratory do not correlate well with data obtained under the operational

condition. Even the original issuers of some of the standards admit that key topics, including technical deficiencies, should be addressed when revising the standards. It is not hard to imagine how costly a questionable standard can be. Suppose a system designer comes up with a new product, performs faithfully a successful compliance test in accordance with this existing questionable standard, and then discovers that the system is still not electromagnetically compatible in the actual operating environment, resulting in performance degradation, product damage, or even personnel injury. This designer will have to find out where the incompatibility is, modify the design, and then perform the same type of tests without assurance that the newly modified system will function properly with full EMC. The procurer of the system ends up paying additional development cost and suffering a long delay in using the final product.

In supporting the electronics industry to fully comply with the EMC standards and to minimize test costs by reducing the measurement uncertainty, the National Institute of Standards and Technology (NIST) is reviewing the existing EMC-related standards and recommendations. We hope to identify the problems and deficiencies associated with some of the current measurement practices, and offer improved alternatives to users, designers, and regulatory or standard-setting agencies. At the same time, we are assessing our own EMC metrology capabilities. If there are inadequacies, we will initiate new metrology programs to provide necessary assistance to the entire EMC community.

In this study, we restrict ourselves to the review of a few important U. S. standards being enforced by the regulatory agencies or incorporated in voluntary industrial practices. The essential points in each standard under review are summarized and described in section 2 with comments. We then discuss them in section 3, based on a set of general technical factors and reasons. Suggestions of whether some of the measurement methods developed at NIST can be used as alternatives in order to obtain more accurate results are also presented in section 3. At the same time, our existing measurement capability and shortcomings are pointed out. Concluding remarks together with possible future EMC metrology programs to be developed by NIST for benefiting the electronic industry are given in section 4. In this review exercise, we concentrate only on radiated emission and susceptibility in view of our own expertise in these areas, even though conducted emission and susceptibility are equally important to some applications.

2. Important EMC Standards and Regulations

Without doubt the U. S. Government has been the largest procurer and user of electronic products and systems. On the military side, the Department of Defense (DoD) has recognized the importance of EMI control and issued many specifications and standards [1]. On the civilian side, the Federal Communications Commission (FCC), under authority of the Communications Act of 1934 and its amendment of 1982, is charged with regulation of the manufacture, import, sale, shipment, and use of electronic devices and products which may either emit to cause interference to radio reception or be affected by the EM environment so that their designed performances are degraded. After conducting many hearings to receive comments from the industry and general public, the FCC frequently issues rules and regulations to enforce EMC [2].

Other U. S. governmental agencies such as the Food and Drug Administration (FDA), Environmental Protection Agency (EPA), and Occupational Safety and Health Administration (OSHA) also impose regulations and standards to implement their own programs. Although these standards are primarily intended for protecting public health and safety, some of them cover EMC-related issues [2].

To comply with the mandatory standards issued by government agencies, U. S. industry and some private organizations frequently publish voluntary EMC recommendations [2] to provide self guidance and promote mutual understanding.

Some of the important standards and recommendations from these governmental and industrial organizations are selected for descriptions and comments as follows.

2.1 Department of Defense Standards

After experiencing many EMI problems over the years, the DoD has published, from time to time, a variety of requirements and standards. Basically, there are three types of documents: (a) principal military EMC standards, (b) supporting military standards, and (c) military handbooks (not compliance documents). For this report, we limit ourselves to reviews of the principal standards [type (a)].

a. MIL-E-6051

This is one of the earliest standards issued by DoD, entitled "Electromagnetic Compatibility Requirements, Systems," whose latest version was dated September 7, 1967. This document is intended primarily for applications to the development of major weapon systems. It emphasizes the overall requirements for EMC at the system (both airborne and ground) level. It specifies control of the EM environment, lightning protection, static electricity, bonding and grounding, degradation criteria and safety margins, and wiring and cabling. In general, anticipated EMC problems are classified into three categories, depending on how serious they are:

Category I -- EMC problems that could result in loss of lives, loss of vehicle, mission aborting, costly delays in launches, or unacceptable reduction in system effectiveness;

Category II -- EMC problems that could result in injury, damage to vehicle, or reduction in system effectiveness;

Category III -- EMC problems that result only in annoyance, minor discomfort, or loss of performance, but not reduction in desired system effectiveness.

This standard also addresses EM hazards to personnel and ordnance. It requires that a system EMC program be established by a contractor with an EMC board to supervise the program, to set degradation criteria and safety margins for each subsystem and equipment after consultation with the procuring authority, to perform the actual EMC tests, and to provide means of expediting solutions of problems. The document does not discuss EM coupling mechanisms through which EMI problems may occur. Test methods are not precisely specified. Expected accuracies in the measurements are not

mentioned. In general, the document is vague and incomplete. It is not easy for users to comply. Success of the standard compliance depends heavily on the EMC program manager's judgement of each contractor.

b. MIL-STD-461

To extend the application of MIL-E-6051 to a single equipment, the MIL-STD-460 series of documents was issued subsequently. The first version, MIL-STD-461, entitled "Electromagnetic Interference Characteristics, Requirements for Equipments," was produced and formally published in 1967 as a result of many committee meetings in DoD. The intent was to improve coordination among the different services and promote unified procurement [1]. Its technical objectives are to ensure that interference control is considered and incorporated into the design of equipment and subsystems, and to provide a basis for evaluating EMC and effectiveness of systems operated in a complex EM environment.

This document was revised on August 1, 1968 to become MIL-STD-461A with the same title. It was then completely reorganized on April 1, 1980, as MIL-STD-461B with a new title, "Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference." This newer version consists of 10 parts, addressing general and specific requirements. The latest edition, MIL-STD-461C, with the same title as 461B, was issued on August 4, 1986 [1]. It has the same basic structure of 10 parts. The major change was the inclusion of a few new test requirements for considering the effects due to EM pulses. As a whole, this document spells out everything in detail. It specifies the emission and susceptibility limits for different classes of equipment, depending on the type (critical, non-critical; dc, ac, or pulse; narrow band or broadband; etc.) and on where they are installed (such as aboard aircraft, launch vehicles, surface ships, submarines, or on ground).

Specific requirements are divided into four categories: conducted emission, conducted susceptibility, radiated emission, and radiated susceptibility. In each category, further divisions are made in accordance with the frequency range or the method involved in the measurement. Details on the allowed emission and susceptibility limits, frequency ranges, and measurement procedures are presented in the next section.

c. MIL-STD-462

This standard, entitled "Electromagnetic Interference Characteristics, Measurement of," issued on July 31, 1967, is considered a companion document of MIL-STD-461. It establishes techniques to be used for the measurement and determination of EMI characteristics (both emission and susceptibility) of electrical, electronic, and electro-mechanical equipment as required in MIL-STD-461C. Test conditions, preparation of test samples, use of measurement apparatus, placement and selection of measuring sensors, frequencies, test setup and configurations, and measurement procedures are all specified. It covers six conducted emission, eight conducted susceptibility, six radiated emission, and four radiated susceptibility measurements [1].

For this report, only those parts of these measurements (radiated emission and susceptibility) which are considered relatively important are described and commented. Specific features and frequency ranges for each

measurement are included. Three of the six radiated emission tests are concerned with unintentional radiations from the major parts of a system under consideration. They are summarized as follows.

(1) Method RE01 is the one recommended for measuring magnetic fields in the frequency range of 30 Hz to 30 kHz radiated from each unit in a given equipment including antenna transmission lines, power cables, and interconnecting wires. The measurement also applies to radiation due to the transmitter fundamental and spurious frequencies, and the oscillator. It specifies a loop antenna (sensor) and an EMI meter as the measuring apparatus. The sensor is to be placed 7 cm from one face of the equipment under test (EUT). The maximum radiated magnetic field for each tuned frequency in the intended range is detected and recorded by varying the sensor's orientation with respect to the EUT and scanning the EMI meter. The measured magnetic field in amperes per meter is then multiplied by the free-space permeability of $4\pi \times 10^{-7}$ H/m to express it in terms of the magnetic flux density in teslas. This value is then compared with the limit specified in MIL-STD-461. The emission limit has been set from 140 dB above 1 pT at 30 Hz to 56 dB above 1 pT for 30 kHz [1]. Whether the measurement takes place inside an enclosure, in a laboratory environment, or in an open site is not mentioned. The required measurement accuracy is not specified. Although magnetic field is the only desired parameter, other important parameters in this measurement, which will affect the measured results, are the size (diameter) of the loop antenna, its orientation with respect to the EUT, its calibration factor, the loop-to-EUT distance, and the environment in which the measurement is made. While the loop-to-EUT distance of 7 cm was recommended from a practical consideration, it certainly has no technical basis. With respect to the intended frequency range, the sensor is placed within the near range of the emitting EUT. Interaction between the emitter and sensor is known to be strong under this condition. A minor change in the distance and orientation of the loop can cause a major deviation in the measured result. Thus, the physical meaning and accuracy of the measured data obtained by a user are doubtful.

(2) Method RE02 is designed for measuring the electric field, in the frequency range of 14 kHz to 10 GHz, radiated from the EUT including cables and interconnecting wiring. Narrowband emissions are measured from 14 kHz to 10 times the highest intentionally generated frequency or 1 GHz, whichever is greater, provided that it does not exceed 10 GHz. For broadband emissions, the measurements are to be made from 14 kHz to 1 GHz. The method recommends that a linear dipole be used as the sensing antenna, for both horizontal and vertical polarizations, together with an EMI meter to record the maximum reading of the radiated electric field. The linear dipole is placed at 1 m from the EUT. The measured maximum electric field is to be compared with the limits specified in MIL-STD-461. For narrowband emissions, these limits vary from 35 dBμV/m (decibels above 1 μV/m) at 14 kHz, decreasing first to 20 dBμV/m at 28 MHz, and then increasing to 60 dBμV/m at 10 GHz. For broadband emissions, the allowable limits vary from 100 dBμV/m/MHz at 14 kHz, decreasing first to 55 dBμV/m/MHz at 200 MHz, and then increasing to 70 dBμV/m/MHz at 1 GHz [1]. For testing nonportable EUTs which are permanently connected either physically or electrically to a vehicle, it also recommends that the EUT be placed on a ground plane. Portable EUTs are to be tested inside a shielded enclosure. Again, the required accuracy is not specified. The parameter to be measured in this method is thus the radiated electric field from an unknown EUT. The other

important parameters, which will change the measurement results, are the dipole length, its polarization, the calibration factor, the dipole-to-EUT distance, the size of the ground plane, and whether or not the measurement is made inside a shielded enclosure. The combined effect of these parameters on the accuracy of the measurement is very difficult to estimate.

(3) Method RE03 is recommended for the measurement of transmitter spurious and harmonic emissions in the radiated field, from 10 kHz to 40 GHz. Specific test frequency ranges are as follows:

EUT Operating Frequency	Test Frequency Range
10 to 30 kHz	10 kHz to 10 MHz
30 to 300 kHz	10 kHz to 100 MHz
0.3 to 3 MHz	10 kHz to 600 MHz
3 to 30 MHz	10 kHz to 1 GHz
30 to 300 MHz	1 MHz to 3 GHz
300 MHz to 1.24 GHz	10 MHz to 12.4 GHz
1.24 GHz and above	Lowest frequency is 200 MHz for coaxial transmission lines, or 0.8 of cutoff frequency for waveguide transmission lines
1.24 to 5 GHz	Upper frequency is 10 GHz (required) or 40 GHz (optional)
above 5 GHz	20 GHz (required) or 40 GHz (optional)

This method may be used together with Method CE06 (conducted emissions from antenna terminals, 10 kHz to 26 GHz). However, the method will apply when the average transmitter output power is greater than 5 kW, the fundamental transmitter frequency is above 1.24 GHz, and the antenna associated with the EUT is an integral part of the transmitter (which cannot be replaced by a dummy load). In addition to an EMI meter, attenuators or amplifiers may be needed for the measurement, and specific antennas (such as rod antennas, biconical antennas, or cavity-backed spirals) depending on the frequency band under 1 GHz are to be used. For frequencies above 1 GHz, it specifies a spectrum analyzer, traveling-wave tube amplifiers, preselector filters, frequency counters, and other various cavity-backed spiral antennas. The measurement is to be performed above a ground plane. It also notes that it may be necessary to make the measurement in a shielded enclosure, because the spectrum analyzer may be susceptible to radiated fields. Furthermore, once the radiated fields at a distance from the transmitter being tested are measured and recorded, the corresponding transmitted power density at the observation point is computed according to the far-field condition. The allowable emission limits on electric field set for this case are 10 V/m for the frequency range from 10 kHz to 30 MHz, 5 V/m from 30 MHz to 10 GHz, and 20 V/m for frequencies above 10 GHz. The required measurement accuracy is not specified. The important parameters in this measurement, which will

affect the measured electric field, are the type and size of the sensing antenna, its polarization, the calibration of antenna or spectrum analyzer, the antenna-to-EUT distance, the environment in which the measurement is made, and the conversion of measured electric fields to power densities based on the far-field condition. Naturally, the measured results depend heavily on one or more of the above parameters. Just the environment factor alone (whether the measurement is performed in a shielded room) could render the measured results meaningless.

The remaining three radiated emission test methods involve unintentional emissions (electric or magnetic field) from vehicles, engine-driven equipment, and overhead power lines in the surrounding area of a test site. No specification on measurement accuracy is given. In all cases, the sensing antennas are recommended to be placed only at a short distance away from the emission source, regardless of the frequency involved. The comments regarding measurement accuracy and physical meaning made for the above three measurement methods also apply here.

The four radiated susceptibility measurements are described as follows.

(4) Method RS01 is recommended for determining whether class I equipment (those which must operate compatibly when installed in critical areas) is susceptible to radiated magnetic fields from 30 Hz to 30 kHz. Cables and connectors attached to the EUT are included. The method requires a loop as the simulated radiating antenna and a signal source capable of producing an approximate magnetic flux density of 50 μT, at a test point 5 cm from the loop face. The plane of the loop is parallel to the plane of the test sample surface. An EMI meter or a narrow-band voltmeter is to be used to verify the anticipated magnetic flux. The susceptibility limits in terms of the magnetic flux density are from 160 dB above 1 pT at 30 Hz decreasing to 78 dB above 1 pT at 30 kHz. The frequencies and the minimum field which causes noticeable susceptibility problems (permanent malfunction or degradation of performance beyond the specified equipment tolerance) in the EUT are recorded. No measurement accuracy is specified. Hence, the measurement parameter is the magnetic field at a distance of 5 cm from the radiating loop, which may cause EMI problem to an EUT. The other important parameters, which will influence the measured results, in this measurement are the loop antenna size, its orientation and calibration, and the distance at which a prespecified magnetic field is produced. Because of large variations in the magnetic field produced by a radiating loop in the near-field environment, a successful test of passing the susceptibility criterion of a given EUT at the distance of 5 cm from the source does not necessarily imply that another test of the same EUT at a greater distance from the same source will again be successful.

(5) Method RS02 is recommended for determining the susceptibility of class I equipment to magnetic induction fields produced by current-carrying wires. The method is intended mainly for testing cables and cases in which an EUT is placed. Two tests, power frequency test and spike test, are required for evaluating both cable and case susceptibility. Specific waveforms and pulse widths are recommended for the tests [1]. No measurement accuracy is required. Besides the measurement parameter of magnetic induction, the other important influencing parameters in this measurement are the cable length, its shielding material, the case dimensions, and the test waveform and pulse width. Combined effect of these parameters could make the measured results unpredictable. Passing of susceptibility test for a cable

of a given length does not warrant passing for another cable of a different length.

(6) Method RS03 is to be used for determining whether or not an EUT exhibits any degradation of performance, malfunctioning, or other undesirable effects when it is immersed in an electric field in the frequency range of 14 kHz to 10 GHz. The recommended susceptibility limits for all surface ships under the U. S. Navy are 10 V/m below decks with metallic hulls, 50 V/m below decks with nonmetallic hulls, and 200 V/m above decks (areas exposed to weather) [1]. This method applies only to class I equipment. It recommends that a signal source, an EMI meter, antennas depending on frequency bands, and an output monitor be used in the measurement. The results consist of recording frequencies at which the EUT is susceptible and the threshold susceptibility level at each frequency. A specific measurement accuracy is not required.

When a large EUT is involved in a testing field, the transmitting antenna is recommended to be placed at a distance sufficiently large from the EUT to allow it to fall within the half-power beamwidth of the antenna. If a very high electric field is to be generated for the lower frequency end, from 14 kHz to 30 MHz, a long-wire antenna installed inside a shielding enclosure is specified. Alternatively, a parallel stripline may be used to generate high, broadband, electric fields. The desired measurement parameter is generation of electric field. The other influencing parameters in this measurement are type and size of the radiating antenna, its orientation, the calibration factor, the size of the intended EUT, the antenna-to-EUT distance, and the susceptibility limit at a specific location. The long-wire antenna is known to be broadband (advantage) but with high radiations from the sidelobe directions (disadvantage). Placing this antenna in a shielded enclosure can produce large variations in electric field produced at a given distance. Passing a susceptibility test of an EUT under this unpredictable field environment is meaningless. Therefore, the recommended measurement practice for low frequencies is not based on a sound technical foundation.

(7) Method RS04 should be employed to determine equipment susceptibility to radiated fields of specified spectral content and intensity in the frequency range of 14 kHz to 30 MHz. A unique feature is the use of a parallel-plate transmission line to produce necessary electric and magnetic fields. It recommends that the EUT be tested with only two orientations when it is placed inside the line. No particular susceptibility limits nor measurement accuracy are specified. Test results include the frequency and the minimum fields to which the EUT is susceptible. The important parameters in this measurement are the method used to produce specified radiated fields, the geometry of the parallel-plate line, and the EUT orientation with respect to the testing fields. While this method is technically more justifiable than the other methods presented so far, the requirement of only two EUT orientations may not be sufficient to determine the overall susceptibility of the EUT, depending on the actual situation involved. Also, the electromagnetic field produced inside an empty parallel-plate line without EUT can be substantially different from that with EUT. It depends on the EUT size relative to the space between the plates. Thus, the susceptibility limit established for a given EUT inside the parallel-plate line can be different from that when it is placed in the actual operational environment. This kind of perturbation effect should be kept in the users' mind when a high degree of accuracy is desired.

This summary covers some of the methods recommended in MIL-STD-462. Five more "Notices" that represent minor additions and modifications, issued at later dates, are also attached to MIL-STD-462 as a package. Another companion standard is MIL-STD-463, entitled "Definitions and Systems of Units, Electromagnetic Interference and Electromagnetic Compatibility Technology," dated June 1, 1977 [1]. This document merely clarifies some commonly used EMI/EMC terminology and emphasizes the use of SI units based on NBS (now NIST) recommendations, even though English units were actually used many times in the standard.

d. MIL-STD-285

This standard, "Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes, Method of," was issued on June 25, 1956 [1]. The document describes a method for measuring the attenuation characteristics of shielding enclosures of different sizes over the frequency range of 100 kHz to 10 GHz. The parameter of interest in this method is, thus, the electric-field or magnetic-field attenuation characteristics or the shielding effectiveness of the enclosure under test. For the sub-band of 150 kHz to 200 kHz, it recommends that a specific signal source, low-impedance vertical loop antennas of 0.3 m in diameter for both transmitting and receiving, and a detector be used to determine the magnetic-field attenuation of the enclosure. The loops are placed 0.3 m away from the enclosure wall.

For the frequency range of 200 kHz to 18 MHz, it recommends that high-impedance rod antennas (also vertical) of 1.04 m in length together with the signal source and detector be used to measure the electric-field attenuation of the enclosure. The rod antennas are placed at a distance of 0.3 m from the enclosure wall.

For the frequency of 400 MHz, it recommends that tuned vertical dipoles be used as the transmitting and receiving antennas with the same set of other apparatus. The transmitting dipole is to be placed at least 1.83 m and the receiving dipole at least 0.05 m away from the enclosure wall.

In all of these three cases, the transmitting antenna is to be placed outside the enclosure with the receiving antenna inside the enclosure during the measurement.

The important influencing parameters in this standard are the size and orientation of the transmitting and receiving antennas, their calibration factors, their respective locations relative to the enclosure wall, frequency, and the wall material. The measurement of attenuation characteristics of an enclosure or of a material is known to depend not only on the enclosure or material itself, but also on the wave type generated by a transmitting antenna (plane wave vs. near-field wave, high-impedance wave vs. low-impedance wave, wave polarization and propagation direction, the environment in which the antenna is placed, etc.), the location and orientation of the receiving antenna and the environment in which it operates, and the calibration factors of both antennas. The response of a receiving antenna placed inside an enclosure represents the vector sum of the direct wave passing through the enclosure and the wave components reflected from the other enclosure walls. As a result, the measurement accuracy of this standard is very questionable. It has been recognized in

the EMC community that users can produce any attenuation results as they please.

e. MIL-STD-1344A, Method 3008

This standard, "Shielding Effectiveness of Multicontact Connectors," issued on August 14, 1981, was prepared for measuring the leakage from the connector-pair interface of a multicontact connector inside a mode-stirred chamber and determining its shielding effectiveness in the frequency range of 1 to 10 GHz. It recommends that a signal source capable of producing an output power of minimum 1 W, an isolator, a frequency counter, a prepared shielded cable, directional couplers, power meters, 50-Ω loads, and attenuators be used as the test apparatus. Long wires are to be used as the input and reference antennas.

Two measurements are made at each frequency to obtain the average power received by the reference antenna and the average power received by the connector, both over one complete revolution of mode-stirrer rotation. The ratio of these two measured results defines the shielding effectiveness of the connector. Measurement accuracy is not specified. The important factors to be considered in this measurement are the selection of sample multicontact connectors, identification of a coupling mechanism with which the field penetrates into the connector, understanding of the field generated inside a mode-stirred chamber, the location of the test sample placed inside the chamber, and interpretation of the measurement results.

The relative uniformity of electric fields generated inside a mode-stirred chamber depends on frequency, the number of modes existing in a given chamber, mode density, chamber dimensions, and the quality factor (Q) as a function of chamber material. While the field uniformity is in general much better than that generated inside a shield enclosure, it still can have a variation as large as 5 to 8 dB, depending on how the chamber is designed.

2.2 Civilian Government Agencies

a. Federal Communications Commission

The major parts of the FCC rules and regulations, as related to EMC, are contained in Title 47, Parts 15, 18, and 68 of the U. S. Code of Federal Regulations, of which Parts 15 and 18 are the relatively important ones [2].

Part 15, "Radio Frequency Devices" (53 pages), defines and sets EMI standards for unlicensed incidental and restricted radiation devices. Operation of any such device without meeting Part 15 provisions is prohibited. Of particular interest is Subpart J, "Computing Devices," which covers EMI limits for class A (commercial, industrial, and business) and class B (consumer) computing devices. Frequency ranges considered for class A are three specific bands: 30 to 88 MHz, 88 to 216 MHz, and 216 to 1000 MHz. The maximum allowable emanations (in terms of electric fields) which may be leaked from these devices at a distance of 30 m are respectively 30, 50, and 70 μV/m. A shorter distance may be used for the measurement if the test results are correlatable with that at 30 m according to the inverse-distance relationship. For class B computing devices the respective maximum allowable radiated electric fields in the same three frequency bands but at a distance of 3 m are 100, 150, and 200 μV/m. If, however, this required distance of 3 m is impractical because of the EUT size and location,

measurements may be made at a further distance up to 30 m and the measured results correlatable with those at 3 m according to the inverse-distance relationship.

The method and procedures for measuring the unintentional emissions from these computing devices are described in FCC/OET (Office of Engineering and Technology) MP-4, "FCC Procedures for Measuring RF Emissions from Computing Devices" (24 pages). It requires that measurements of radiated emission be made in an open flat area. A ground screen is highly recommended, but not mandatory. If a radiating device or equipment cannot be set up on an open-field test site, testing is permitted at the user's premises. In this case, both the equipment and its location are considered the EUT. The measured emissions are then unique to that particular installation.

This standard also recommends that a tuned half-wave dipole antenna be used for measuring the radiated electric field over the entire frequency range of 30 to 1000 MHz. Measurement accuracy is not specified. At the lower frequency end such as 30 MHz, the dipole length will be 5 m, which is too long to be practical. In this or other cases, a different linearly polarized antenna may be used, provided that the result obtained with such an antenna is correlatable with that obtained with a tuned half-wave dipole. The antenna must be capable of measuring both horizontal and vertical polarizations. The antenna height (measured from the feed point) above ground is to be varied, dependent on the horizontal antenna-to-EUT distance, in order to measure the maximum radiated strength. For measurement distances up to and including 10 m, the antenna height is varied from 1 to 4 m. At a distance of 30 m, the antenna height is varied from 2 to 6 m. At intermediate distances from 10 m to 30 m, it may be necessary to adjust the minimum antenna height down to 1 m, except that, for vertical polarization, the minimum antenna height has to be increased so that the bottom half of the dipole clears the site ground surface by at least 25 cm.

Radiated measurements made inside a shielded enclosure are suitable only for determining the frequency of each emission from an EUT. Measured results of electric field in the enclosure environment vary substantially because of multiple reflections of the emission from enclosure walls, and, therefore, are not reliable.

The important parameters relevant to this standard include the size of ground screen if needed, the antenna calibration factor, antenna locations relative to the EUT, EUT configurations, and test environment. Response at the receiving dipole is a vector sum of the emission radiated directly from an EUT placed in the open ground and the emission from the EUT's ground image. Consequently, the final result depends on earth constants (mostly conductivity and permittivity) and the size and design of the ground screen. Furthermore, how the receiving dipole is calibrated is also important in determining the measurement accuracy. In general, a commercially available dipole is almost exclusively calibrated in the far field. The effect on measurement accuracy when the dipole is placed within the near-field range of the EUT is usually not estimated. The environment in the surrounding area of an open site, such as scattering objects, obstacles, vegetation and others is another important factor to be considered in this method of measurement.

Recently, FCC proposed adopting ANSI C63.4 (see section 2.3) as its official measurement standard for digital devices to replace its own MP-4 [3-4].

Part 18, "Industrial, Scientific and Medical Equipment" (7 pages), sets the EMI emission limits for the industrial, scientific, and medical (ISM) equipment, which may be operated on any frequency above 9 kHz except a few prohibited bands, which are reserved for safety, search, and rescue purposes: 490 to 510 kHz, 2.17 to 2.194 MHz, 8.354 to 8.374 MHz, 121.4 to 121.6 MHz, 156.7 to 156.9 MHz, and 242.8 to 243.2 MHz. The ISM equipment operating on a set of specific frequencies (6.78, 13.56, 27.12, 40.68, 915 MHz; 2.45, 5.8, 24.125, 61.25, 122.5, and 245 GHz with certain small tolerances) is allowed unlimited radiation. This could cause EMI problems to other co-located equipment. The average annual number of verified complaints on interference from ISM equipment during the past few years is a little over 100. It represents only about 0.14% of the total annual number of verified complaints from all man-made sources of interference. For other frequencies, there are some limits. But the maximum allowable radiated electric-field limits are, in general, less restrictive than those in Part 15. Technical standards on frequency tolerance and field limits are detailed in Subpart C. The measurement techniques to be used to determine compliance with the requirement are described in MP-5, "Methods of Measurements of Radio Noise Emissions from ISM Equipment."

Part 68, "Connection of Terminal Equipment to the Telephone Network" (146 pages), provides uniform standards for protection of telephone network from terminal equipment and the associated wiring. It also discusses the problem of compatibility of hearing aids with the telephone system. Basically, the problems addressed in Part 68 are conducted (rather than radiated) EMC in nature.

b. Food and Drug Administration

This agency, under the Center for Devices and Radiological Health (CDRH) of the U. S. Department of Health and Human Services, develops and implements national programs for protecting public health concerning medical devices and radiological technology. Most of their standards are related to health issues. There are, however, a few EMC-related topics such as the performance standards for electronic, ionizing radiation, and microwave/rf emitting products, which are included in Title 21, "Food and Drugs" (9 volumes), Subchapter J. Another document of EMC interest is MDS-201-0004, "Electromagnetic Compatibility Standards for Medical Devices" (62 pages), which covers emission and susceptibility requirements and test methods for medical devices [2]. Some restrictions on emissions from medical devices should, perhaps, be imposed in view of the fact that FCC allows unlimited radiations for certain frequency bands from the ISM equipment. One more publication, FDA 87-4219, "Medical Devices Standards Activities Report," provides a comprehensive listing of national and international, voluntary, and regulatory standards activities for medical devices.

c. Environmental Protection Agency and Others

The EPA exercises statutory authority in providing public safety in the areas of toxic substances, clean water, energy, and clean air. The three documents issued by EPA [2],

SAR No. 1161, "Guidance for Occupational Radiation Exposure,"

SAR No. 1525, "Radiofrequency Radiation Guidance," and

EPA 2663, "Biological Effects of Radiofrequency Radiation,"

address the health-related issues which also have EMC impacts. Specifically, the effects of radiated fields on human health are of their concern. While experimental studies in this area under the support of EPA have been performed for many years, no reports concerning solid evidences of long-term low-level exposure of radiated fields on human health have been issued.

Other government agencies such as the National Institute for Occupational Safety and Health in the U. S. Department of Labor also, from time to time, issue regulations regarding safety. These regulations may also have EMC consequences, but are not considered as important as those by FCC.

2.3 Voluntary Organizations

Because the standards suggested by the organizations to be described in this section are voluntary, the working committees under these organizations wisely concentrated on recommendations of measurement methods, experimental setups, designs and arrangement of components to reduce rf emissions or to increase immunity, and performance requirements of instruments, rather than recommendations of specific emission and immunity limits as in MIL-STD-461. Setting <u>emission</u> limits may be useful in practice, because the ultimate goal is to encourage reducing unnecessary leakage which can cause interference problems to others. It is much more difficult to specify realistic <u>immunity</u> limits because of the dependence of actual environment under which a device or system is to be operated. A more practical approach is to determine the susceptibility (or immunity) of an electronic product based on a good measurement method and then to determine whether this product can function normally in a given EM environment.

a. American National Standards Institute

Founded in 1918, ANSI is an association of industrial concerns, trade organizations, technical societies, labor and consumer organizations, and government agencies. It recommends national voluntary standards in safety, engineering, and technical fields. It also offers information on foreign standards and represents the United States in international standardization coordinations. The standards issued by ANSI are usually the products of many working committees. Of particular interest to EMC community is Committee C63 (Radio-Electrical Coordination).

The standard C63.2-1987, "Electromagnetic Noise and Field Strength, 10 kHz to 40 GHz -- Specifications," describes the requirements for instrumentation used to measure peak, quasi-peak, rms, or average values of

EM noise and fields in the indicated frequency range. The basic apparatus is a frequency-selective voltmeter. With appropriate coupling devices such as antennas and current probes, the instrument also measures other physical quantities such as the current and voltage. The required measurement accuracies are ±2 dB in voltmeter, ±3 dB in field strength, and ±2% in frequency. It recommends that different antennas be used as radiated field sensors in different frequency bands. They are rod or loop antenna (0.01 to 30 MHz), tuned dipole antenna (30 to 1000 MHz), biconical antenna (30 to 220 MHz), log-periodic and conical log-spiral (220 to 1000 MHz), conical log-spiral (1 to 10 GHz), double-ridged waveguide (1 to 18 GHz), and matched waveguide horn (18 to 40 GHz). While these antennas are adequate to cover the entire intended frequency range, consistency in calibrating various antennas in different operating environments is still a problem area. Ideally, antennas with much broader frequency band of operation to reduce the required number of sensors are needed.

The standard C63.4-1981, "Radio Noise Emission from Low-Voltage Electrical and Electronic Equipment in the Range of 10 kHz to 1 GHz," sets forth uniform methods for measuring radiated and power-line conducted radio noise emitted from this category of equipment in the indicated frequency range. The methods apply to the measurement of individual components and units, subsystems, or systems. It also specifies for the test site environment an open field with an elliptically shaped ground plane free of reflecting objects as the condition to ensure valid, repeatable measurement results. The ambient noise and other undesired signals should be at least 6 dB below the allowable limit of the applicable standard when the EUT is de-energized. By comparison to the FCC standard, this standard is issued after more careful technical considerations. This standard also specifies an alternative measurement environment (shielded enclosure) for frequencies below its lowest resonant frequency. Measurements made inside the enclosure are permitted at a distance of 1 m between the EUT and sensor. The measurement data may be extrapolated to other distances only if the extrapolation can be shown to produce <u>valid</u> results. What constitutes validity is, however, not clearly shown. In view of the comments made earlier, it is doubtful that measurement results obtained in a shielded enclosure can be considered valid. The most recent version of this standard was dated in 1991. The part concerning the measurement for digital devices has been adopted by FCC to replace FCC MP-4 [3-4].

The standard C63.12-1984, "Procedures for Control of System Electromagnetic Compatibility, Recommended Practice on," discusses the nature of both man-made and natural environmental rf noise, identifies several types of devices used for measuring the noise, and suggests limits for emission and susceptibility subject to various environmental constraints. To the extent that rf noise varies in time and space, a statistical means is, perhaps, the best method used to describe it.

Another ANSI Committee C95 on Radiation Hazards dealing exclusively with health issues no longer exists. Its main function is now carried in IEEE Standards Coordinating Committee SCC-28 on Non-Ionizing Radiation. One of the standards published by the old Committee C95 is C95.1-1982, "Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 300 kHz to 100 GHz." This standard recommends protection guides to prevent biological injury from exposure to EM radiation in the indicated frequency range. These recommendations are intended to apply to non-occupational as well as occupational exposures. In terms of the mean

squared electric field (E^2), the mean squared magnetic field (H^2), and the equivalent far-field free-space power density (S), the recommended exposure limits are as follows:

Frequency Range (MHz)	E^2 (V^2/m^2)	H^2 (A^2/m^2)	S (mW/cm^2)
0.3 - 3	400 000	2.5	100
3 - 30	4 000 ($900/f^2$)	0.025 ($900/f^2$)	$900/f^2$
30 - 300	4 000	0.025	1
300 - 1 500	4 000 (f/300)	0.025 (f/300)	f/300
1 500 - 100 000	20 000	0.125	5

The frequency f in the above table is expressed in megahertz. This standard, while on a much conservative protection level as compared to other international standards, can be used to supplement the EPA standard described above.

In addition, ANSI also publishes standards jointly with the Institute of Electrical and Electronics Engineers (IEEE). Examples are:

ANSI/IEEE Standard 748-1979, "IEEE Standard for Spectrum Analyzers,"

and

ANSI/IEEE Standard 430-1986, "Measurement of Radio Noise from Overhead Power Lines and Substations, Standard Procedures for the."

b. American Society for Testing and Materials

The ASTM has become one of the largest voluntary standards organization in the world with more than 32 000 members. It publishes test methods, specifications, practices, guides, and classifications for materials. The EMC/EMI aspect of its work is the responsibility of subcommittee D09.12 on Electrical Tests, under Committee D9 on Electrical and Electronic Insulating Materials. Its recent standard, D 4935-89, "Standard Test Method for Measuring the Electromagnetic Shielding Effectiveness of Planar Materials," was issued based on the far-field method as recommended by NIST [5-7]. This is a much more meaningful standard than MIL-STD-285. A method for measuring the same material in a near-field environment and one for measuring shielding effectiveness of containers and gaskets are still needed.

c. Institute of Electrical and Electronics Engineers

The IEEE standards are normally developed by the technical committees of its various Societies and the Standards Coordinating Committees. The EMC-related standards are usually prepared by the committees under its Society of Electromagnetic Compatibility. Sample rf standards are [2]:

IEEE Standard 140-1950, "Minimization of Interference from RF Heating Equipment, Recommended Practice for,"

IEEE Standard 139-1952, "Field Intensity above 300 MHz for RF Industrial, Scientific and Medical Instruments, Recommended Practice for Measurement of," and

IEEE Standard 299-1969, "High Performance Shielding Enclosures, Trial-Use Recommended Practice for Measurement of Shielding Effectiveness."

The first document reviews the theoretical aspects of the EMI problem due to rf heating equipment and outlines procedures and required instruments for measuring emissions in the frequency range from 20 kHz to 200 MHz. Some remedial means for reducing the emission in order to comply with the FCC rules are also suggested.

The second document is aimed specifically at ISM equipment. Topics include measurement methods, antenna design, receivers, other measuring equipment, and precautions for ensuring measurement accuracy. This standard is very useful to determine the emission for frequencies above 300 MHz, especially in view of the fact that Part 18 of the FCC standard allows unlimited radiation from ISM equipment for some frequency bands in the frequency range outlined in this standard.

The third standard recommends uniform test procedures and estimation techniques to determine the effectiveness of room-sized high-performance shielding enclosures over three frequency bands: from 100 Hz to 20 MHz, from 300 MHz to 1 GHz, and from 1.7 to 12.4 GHz. In the lowest frequency band, small and large loops are used for measuring the magnetic field near the enclosure wall. In the middle frequency band, dipole-to-dipole tests for measuring the electric field are delineated. For the highest frequency band, power measurements are recommended. Recognizing the dependence of measured results on frequency and position of the sensor, the committee preparing this standard emphasizes that the measured result only represents the shielding effectiveness for that specific test and procedure. Some tests and procedures even require multiple measurements of a similar performance feature at different locations or with different polarizations. For a given procedure, the minimum and average shielding effectiveness will be reported. Clearly, this standard is more carefully drafted as compared to MIL-STD-285. However, this standard is still not general enough for accurately determining the shielding effectiveness of an enclosure.

d. Society of Automotive Engineers

The SAE, founded in 1905, is a nonprofit organization dedicated to "the advancement of mobility technology to better serve humanity." It develops technical information on all forms of self-propelled vehicles and disseminates such information through meetings and reports. All documents prepared by SAE are submitted to ANSI for recognition as possible ANSI standards. Although compliance with SAE standards is voluntary, nearly 200 of them have been adopted by DoD as mandatory. SAE has also been an important source of aerospace standards through its Aerospace Engine Division.

The EMC issues are addressed by SAE Committee AE-4, which assists the technical community with standardization and improved design and test methodology. It emphasizes the concept of "design before fact." Committee AE-4 has published various documents applicable to vehicular EMC. Of particular interest is the SAE Aerospace EMC Handbook, which is a collection of AIRs (aerospace information reports) and ARPs (aerospace recommended practices). Some important ones include [2]:

SAE AIR 1209, "Construction and Calibration of Parallel Plate Transmission Line for EMI Susceptibility Testing,"

SAE AIR 1255, "Spectrum Analyzers for EMI Measurements," and

SAE AIR 1509, "EMC Antennas and Antenna Factors: How to Use Them?"

The other well-known standard, SAE J1113, "Electromagnetic Susceptibility Procedures for Vehicle Components (except Aircraft)," was developed by the SAE Subcommittee on EMI Standards and Test Methods. It discusses the measurement methods and requirements for determining the susceptibility of vehicle systems to radiated magnetic and electric fields in different frequency bands. Generally, it includes more technical aspects than those in FCC regulations. In particular, one section recommends that a transverse electromagnetic (TEM) cell be used for determining the electric-field susceptibility of equipment for frequencies from 14 kHz to 200 MHz. Another section covers the requirements for determining susceptibility of automotive electronic equipment, subsystems, and systems to electrostatic discharges (ESD). In this latter aspect, it recommends an ESD test by direct contact.

e. Radio Technical Commission for Aeronautics

The standards issued by the RTCA are mainly related to aviation, air traffic control, and communications. Its activity in the EMC area is focused on rf interference to aeronautical radio systems. It has published three well-received documents [2]:

DO-119, "Interference to Aircraft Electronic Equipment from Devices Carried Aboard,"

DO-127, "Standard Procedure for the Measurement of the RF Radiation from Aviation Radio Receivers Operating within 30-890 MHz," and

DO-160C, "Environmental Conditions and Test Procedures for Airborne Equipment."

The first document listed above recommends that permissible rf radiation from portable equipment used in flight be limited to avoid interference with the aircraft operating equipment. The second one recommends that a far-field method be used for making necessary measurement in that particular frequency range. Section 20 of the third standard describes the tests for determining whether equipment will operate within performance specifications when the equipment and its interconnecting wiring are exposed to rf modulated power, either by a radiated field or by injection probe induction onto the power lines and interface circuit wiring. Whether these test methods will produce equivalent results are not seriously addressed.

f. Electronic Industries Association

The EIA represents electronics manufacturers in all categories. Its 250 standing committees have produced more than 500 EIA engineering standards. The EIA Government EMC Committee, G-46, serves as an advocate of industrial positions regarding government specifications, standards, and regulations. Its duties include reviewing and coordinating related

activities by government, industry, and its members to make sure that EMC-oriented regulations and standards are adequate and appropriate. It also makes proposals and recommendations for actions. Quite often government agencies also submit proposed regulations for EIA reviews and comments.

One of the EIA standards, EIA-378, "Measurement of Spurious Radiation from FM and TV Broadcast Receivers in the Frequency Range of 100 to 1000 MHz, Using the EIA-Laurel Broadband Antenna," was issued in response to the commonly recognized fact that the local oscillators and other components of superheterodyne receivers in broadcasting stations can be sources of spurious radiations and cause interference to others. This standard describes setups and techniques for measuring these radiations.

g. Computer and Business Equipment Manufacturers Association

The products made by the member companies represented by the CBEMA constitute almost 4% of the U. S. gross national product. Although CBEMA does not directly publish standards, its members work closely with other voluntary organizations such as ANSI and IEEE to offer input information, guidance, and opinion. The subcommittee SC5 on EMI of its Environment and Safety Committee published a report in 1977, "Limits and Methods of Measurement of Electromagnetic Emanations from Electronic Data Processing Equipment" [2]. Although this report is not a standard, it can be used as a valuable reference or supplementary document when considering FCC Part 15.

h. Others

Another widely recognized organization, Underwriters Laboratories (UL), lists products and systems made by various industries, that have been evaluated by them for hazards to life and property. It issues frequently the basic engineering requirements for the products under various categories. These requirements are based on sound engineering principles, research results, tests, and field experience. Its activity in EMC, however, is limited to simple facilities such as a roof-top ground screen for calibrating antennas and for measuring emissions from electronic products.

3. General Discussions of Existing Standards

After describing the key existing EMC standards with brief comments, we now offer in this section detailed technical discussions and analysis that may help reduce or eliminate some of these EMI problems when taken into consideration for the revision of the standards. In this exercise, we suggest some measurement techniques developed at NIST, which may be used as alternatives to those in the existing standards in order to obtain more accurate results. At the same time, our EMC metrology and service capability for supporting the electronic industry is appraised. New research and measurement programs are also identified to strengthen our position to provide better services to the EMC community.

3.1 Setting a Realistic Standard Limit

As was emphasized in the introduction of this report, an EM susceptibility limit should be set to represent the actual EM environment in which the equipment is to be operated. For a confined location such as on a military surface ship or inside an aircraft, many intentional sources

including various antennas and transmitters are designed and installed for meeting certain objectives. The EM fields generated by these sources in the sidelobe regions, together with the fields from unintentional sources, are time varying in that not all sources may be emitting simultaneously. Conservatively, a worst case based on the set of available information on frequency, power, distance, direction, and time of operation may be adopted as the susceptibility limit. In some cases in an enclosed environment such as aircraft or helicopters, the effects of resonant frequencies and their corresponding quality factors (Q) should also be analyzed and taken into consideration. Furthermore, for special localities such as those areas surrounding major airports, various radars for different purposes and other emitting sources are present. A reliable method, based either on a theoretical model or on actual measurement data, for determining a realistic field environment is important for the aerospace industry. The results of fields may be expressed in terms of peak or average values with a prescribed accuracy limit and degree of confidence. This type of information is to be used by the aerospace industry to evaluate whether the electronics aboard the aircraft are compatible with that particular field environment. Deriving a statistical model for characterizing the field environment near major airports, based on published knowledge on the topic through literature survey or by modified methods, deserves to be considered one of our future research activities.

For other locations not so confined or well defined, it may be hard to specify a realistic susceptibility limit. When a limit is over-specified, it will ensure EMC even though it may cost users unnecessarily. On the other hand, if a limit is under-specified, an EMI problem will result. A case in this category is evidenced by the recent incident related to the U. S. Army Apache Helicopter program [8]. This helicopter was primarily designed as an airborne anti-tank weapon, a $13 billion project. Since production began in January, 1984, approximately 700 of the projected 807 total production have been delivered to the Army. According to the specifications contained in MIL-STD-462, equipment and subsystems intended for use in aircraft purchased by the U. S. Navy and Air Force are expected to meet the rather strict susceptibility (or immunity) limit of 200 V/m for electric fields (because of their special, confined operating location where so many high-power sources are present). However, for the aircraft ordered by the Army, an immunity limit of 20 V/m may be specified because of their typical operating environment. This lower immunity limit was actually used in the Army Apache Helicopter program. As a consequence, a severe EMI compatibility problem has been discovered. Specifically, EMI causes uncommanded stabilator movement and other difficulties in the automatic flight control system, vertical instrumentation display system, ac and dc power systems, fire detection system, blade de-icer system, and command instrument system. In fact, the helicopter experiences EMI problems even when operated in radiated fields from low-level emitters such as commercial microwave devices, television stations, and airport radars [8].

The modernization effort of military hardware is continuing and is often achieved by adding transmitters with higher power and better signal processors with lower power requirements, EMI problems will likely be experienced more frequently in the future if susceptibility limits are not realistically established.

3.2 Estimating Measurement Uncertainties

The most serious deficiency in existing standards is perhaps a lack of technical basis for estimating measurement uncertainties. This explains why so many measurements recommended in the standards fail to yield repeatable results within the uncertainty. When the actual results of the same measurement under the same condition vary by a large amount of, say, ±40 dB such as those experienced with the emission and susceptibility measurements made inside a shielded enclosure or with the shielding effectiveness measurement of materials and enclosures, the measurements as specified in the standard are obviously useless. However, a required uncertainty for certain measurements cannot be prespecified in general. This is so because it may never be realizable. The important issue is to be able to estimate measurement uncertainties for a given measurement method and environment based on technical reasons or theoretical computations. A comparison of experimental and computational results is always helpful. Uncertainties due to equipment imperfection, technical difficulties, or unrealistic assumptions included in the theoretical models may then be analyzed and estimated. Changes in the measured data due to changes in one or more measurement parameters should be predictable. Similarly, estimates of changes in characteristics of EUTs from a laboratory environment to a field environment should also be made. These factors should be taken into consideration when revising the standards in the future.

3.3 Determining Specifications Based on Technical Justifications

A closer examination of the specifications contained in the standards reveals again that the most serious shortcomings are often due to a lack of understanding of the EM coupling mechanisms and the antenna characteristics in different environment (such as far-field or near-field). The specifications, therefore, do not rest on a sound technical basis. Some examples are discussed as follows.

a. Separation between Antenna and EUT

In many measurement methods suggested in MIL-STD-462, such as Methods RE01 and RS01 for determining the emission and susceptibility of radiated magnetic fields, only small separations such as 7 cm or 5 cm between the EUT and a sensor for RE01 (or a radiator for RS01) were specified. While this specification of separation may be due to practical considerations, these distances are obviously electrically short for the intended frequency range of 30 Hz to 30 kHz. When the EUT and a sensor (or a radiator) are within the near-field region of each other, the field structure at the sensor or radiator is very complex and sensitive to minor changes in distances or other parameters. Further, the coupling between the EUT and sensor (or radiator) is more severe when the separation is so short. This is one of the reasons why many measurement results do not agree with each other.

Two stable and reliable methods developed at NIST are based on sound theoretical considerations and involve a TEM cell or three orthogonal loops to achieve the same purpose. Since both the TEM cell and loop antennas are good primarily for low frequencies, they are suitable for this application. For determining the magnetic field radiated from an unknown source, the EUT under investigation is placed inside a TEM cell and rotated systematically. Measurements of the difference power outputs from the two ends of the TEM

cell will yield a set of equivalent magnetic dipole moments to represent the EUT, from which the corresponding radiated magnetic field in free space can then be calculated [9, 10]. This method will eliminate the problem due to a short separation of 7 cm in Method RE01. In fact, another advantage is that no sensing antenna is needed in this case. This same method yields simultaneously the equivalent electric dipole moments and hence the electric field radiated by the same unknown EUT at low frequencies if the sum power outputs of the TEM cell are measured. This method also eliminates the specification of 1 m for the separation as recommended in Method RE02 and thus can be used to replace the arbitrary requirement of separation distance in that method and Method RE03 (low-frequency portion). The use of a shielded enclosure as recommended in Method RE03 and ANSI C63.4 can also be avoided, thereby eliminating the reflection problem due to the enclosure walls. In addition, the total power radiated by the EUT and the maximum power density produced by it at a specific point of space can all be determined by this method.

Alternatively, placing the unknown EUT at the center of a doubly loaded loop antenna in a given plane (say, the xy plane) and then rotating the loops in two extra orthogonal orientations (the yz and zx planes) will realize the same objective for determining the low-frequency magnetic field and total power radiated by the EUT [11] as in Method RE01, but on a much firmer basis.

For determining the EUT's susceptibility to radiated magnetic field, radiated electric field, or both, the TEM cell method can also be applied advantageously. When a TEM cell is fed from one end and is terminated with a matched load on the other end, a plane wave is generated inside the cell. This method can be used to replace Method RS04, where a parallel-plate transmission line was specified for this measurement. A parallel-plate line is susceptible through its side opening, however, to other potential interferences. Furthermore, because only two orientations were recommended in Method RS04, its measurements may not be as complete for assessing the EUT's susceptibility characteristics as the TEM cell method.

When the receiving port of a TEM cell remains open, a field environment with dominant electric field but negligible magnetic field can be generated near the center of the cell [12]. This arrangement is suitable for testing the EUT's susceptibility to electric fields and thus can be used to replace Method RS03. On the other hand, if the receiving port of a TEM cell is shorted, a different field environment with dominant magnetic field but negligible electric field can be created [12] to replace Methods RS01 and RS02 for testing the EUT's susceptibility to magnetic fields. These two methods apply only to lower frequencies below the cut-off frequency of a TEM cell determined by its size. Related issues such as measurement uncertainties and perturbation effects due to the presence of EUT inside the TEM cell are also discussed in these alternative methods. Thus, in low-frequency emission and susceptibility measurements, the capabilities and facilities at NIST are more than adequate to meet the industrial need.

To verify the suggested alternative methods for measurements, we should perhaps do more work by selecting a known device as our EUT to be measured by these alternative methods for both emissions and susceptibility (or immunity), and then compare the results with those obtained according to MIL-STD-462. A meaningful assessment may then be made in a quantitative manner.

For testing EUT's susceptibility to electric fields at higher frequencies, as in Method RS03, a better facility such as an anechoic chamber is suitable with much stronger technical justification. The chamber at NIST designed for the frequency range of 200 MHz to 40 GHz can be used for this purpose [13]. Characteristics of this chamber including quality of the fields generated at the test zone by standard antennas, uncertainty estimates, and near-field corrections have all been analyzed.

Part 15 of the FCC standards specifies that a sensing dipole antenna be placed at the respective distances of 30 m and 3 m away from Class A and Class B computing devices for measuring the electric field leakage from these devices at three different frequency bands. When these distances are not met because of practical limitations, determination of electric fields from measurements at a shorter distance (or a longer distance up to 30 m) and based on the inverse-distance relationship was recommended. Again, a shorter distance may put the sensing dipole within the near-field range (dependent on the actual frequency) from the emitting computing devices. Under this condition, the inverse-distance relationship will not apply, and the derived electric field will not accurately represent the actual emission, thus resulting in errors. This same comment applies to some of the ANSI standards as well.

Generally speaking, more reliable measurements (TEM cell or anechoic chamber depending on the size of an EUT and frequency) are required for determining more accurately the emission and immunity of electronic components and subsystems. Therefore, understanding and physical interpretations of the measured data under different conditions are also important for the final EMC analysis.

b. Shielded Enclosure

Shielded enclosures of rectangular cross section are frequently recommended in the existing standards such as in Method RE03 and ANSI C63.4 for measuring the emissions from an EUT. The same recommendation has also been made for measuring rf susceptibility of equipment in order to generate very high fields inside the enclosure without causing interference to nearby equipment. This technique, while good from the security point of view, has caused major disagreements among the users. The main reason is that the direct-path radiation from an EUT placed inside the enclosure is added vectorially to the reflections from enclosure walls. The final vector sum may be significantly different from the direct-path result, depending on the phase differences resulting from different path lengths. The deviation between the combined vector sum and the direct-path result may be as large as 40 dB. A small change in the distance between an EUT and a sensor can result in a large difference in the final measured result. After this fundamental deficiency was discovered, using rf absorbing materials inside the enclosure was suggested as a remedial means for reducing the effect of reflection. While this remedy is proven effective in many cases, it still cannot yield repeatable measurement results within a small tolerance because the size (frequency dependent) and number of absorbing panels and their exact locations inside the enclosure result in different effects. In addition, the metal shielded enclosure also behaves as a rectangular cavity with a high quality factor (Q). Strong field amplification occurs at different resonant frequencies, making comparison of the measurement results meaningless.

A serious assessment of the measurement error bound incurred in a typical shielded enclosure as specified in MIL-STD-462 was made by NIST [14] together with a suggestion of alternative techniques for using the same enclosure [15]. A more viable technique, based on theoretical understanding, would be the use of a reverberating chamber. Such chambers have been extensively investigated by NIST [13, 16, 17]. All the advantages associated with the shielded chamber, such as security considerations and generation of high fields inside the enclosure without causing interferences to exterior equipment, are retained. An existing conventional shielded enclosure can be converted to a reverberating chamber with the addition of extra parts and devices such as a mode stirrer, a motor, and other necessary items.

With the size of 2.74 m x 3.05 m x 4.57 m, our reverberating chamber can be operated at a frequency as low as 200 MHz. The measurement uncertainty is about 5 to 7 dB, which, although still high, represents a significant improvement over the conventional shielded enclosure. Results of rf susceptibility for various components and systems measured inside the NIST reverberating chamber have been found comparable, within a certain difference, to that obtained inside an anechoic chamber. The difference is attributed mainly to the EUT's gain as a receiving antenna. The input power requirement for the reverberating chamber is, however, much less than that for the anechoic chamber to produce the same testing field. Comparison of our measured results with that obtained from other reverberating chamber of different sizes has also been made and found to be in good agreement. This chamber offers a good NIST facility for meeting the requirement of high-frequency susceptibility testing. We should extend our research work in this area toward much lower-frequency applications in the near future.

c. Site Attenuation

Many measurements in the current standards such as Method RE03 in MIL-STD-462, FCC Part 15, and ANSI C63.4 require a good ground screen for performing open-field tests. The quality of a ground screen may be characterized by a factor called site attenuation, which is based on the concept of minimum insertion loss. However, the mathematical definitions for site attenuation as used by the FCC, International Electrotechnical Commission, and NIST are different, depending on the condition assumed in the derivation [13]. Practically, the ground must be well constructed with a large size so that it may approach the ideal case where the amplitude of the ground reflection coefficient is 1 for both horizontal and vertical polarizations as is normally assumed in theoretical formulations. The often used simple roof-top space without the reinforcement of additional metal screens may not be adequate to meet this condition, even though providing a metal screen is not mandatory in the FCC standard. A method of measurement yielding good results on site attenuation as suggested by NIST can be found in the literature [18]. Measured results have been found to be in good agreement with theoretical results. The one used at NIST is a 30 m x 60 m wire mesh ground. The frequency range is approximately from 30 kHz to 1 GHz. This ground, as well as a set of well characterized dipoles with adjustable lengths and other ancillary equipment, represents a good reliable measurement facility. It has been frequently used for calibrating antennas and measuring emissions from unknown sources by our customers or by ourselves.

The quality of the open site used for measurements is also critical. It should be beneficial to the EMC community if an existing site, after a thorough evaluation and characterization, is designated as the standard site. A new site to be built by others can be evaluated by a standard method and its characteristics compared with those of the standard site. This exercise will enhance measurement repeatability.

d. Far-Field vs. Near-Field Conditions

We already mentioned some potential errors which may occur for certain low-frequency cases when an inverse-distance relationship is applied, in compliance with the FCC Part 15 requirements, for converting the measured electric field at a shorter distance from the computing devices to a distance of 3 m. In addition, the antenna factor provided by antenna manufacturers to be used in the measurement is exclusively calibrated under the far-field condition. Since the antenna characteristics differ in far-field and near-field regions, a direct application of the far-field antenna calibration curve to the measurement of emitted fields in a near-field situation will also produce some errors in interpreting the measurement results. Thus, a correction factor based on measurements, computations, or both should be included in the actual measurements to compensate for the difference. Some preliminary work in this area at NIST has already begun [19]. More systematic analyses and measurements for calibrating antennas in a near-field environment should also be done. Furthermore, in the computation of antenna factor for a linear dipole antenna, the sinusoidal current distribution on the dipole has normally been assumed, for simplicity, in the EMC community. Strictly speaking, this assumption is accurate only for an infinitely thin dipole with the dipole length no more than a half wavelength with respect to the frequency of interest. For a thicker or a longer dipole, a more realistic current distribution should be used to yield better results for the antenna factor [20]. Even though this consideration may only yield a minor improvement in accuracy, some work in this area together with the effect of mutual impedances between dipoles on the current distribution may be carried out for making a quantitative analysis.

Other commonly used antennas in the dipole family such as top-loaded antennas and bow-tie antennas should also be analyzed more carefully based on good theoretical models before a calibration curve is generated for application.

In general, better low-frequency antenna calibrations could be achieved by taking the above factors into consideration.

e. Shielding Effectiveness

To achieve EMC an extra shielding material is often provided to protect the vulnerable parts in a system. The shielding properties of a material with respect to the radiated electric and magnetic fields are dependent strongly on frequency, space, and polarization of the interfering fields. The measured results on shielding materials also depend on the specific setup, instrumentation, and type of antennas used in the experiment [5,6]. Because of a lack of thorough understanding of the coupling theory, many questionable measurements recommended to meet the requirements in MIL-STD-285 have been suggested and included in the standards to yield erroneous information on shielding effectiveness (SE). In fact, consistent results

based on those recommended measurements have never been obtained. Thus, the true SE of many commercial materials was not positively determined by a reliable method of measurement until 1989, when ASTM formally adopted the method of measuring SEs of planar materials as proposed by NIST [21]. This method is based on the far-field concept. Related background studies from both theoretical and experimental considerations are found elsewhere [5]. Studies for evaluating the SE of materials in a near-field environment should also be done with the objective of establishing another measurement standard under this particular situation. Measurements, based on theoretical understanding, for evaluating the SE of containers or enclosures to complement IEEE Standard 299-1969 and the SE of gaskets have not been available. Further study in these areas by NIST is thus desirable.

f. Probe Requirements

To verify the emission limits as required in many standards, different antennas for different frequency bands have been recommended for measurement. Some of these antennas are physically large. The true field structure appearing at a particular region in space as emitted from an unknown EUT is often disturbed by the presence of such a large measuring antenna. This will cause inaccuracy in the measurement. Thus, a broadband antenna with a much smaller physical size (a probe), together with an optical sensing system to minimize the disturbance would be ideal. That is why NIST has developed a few broadband probes for this purpose [22-24]. The latest probe model has its dipole length as small as 2 mm with a theoretical upper frequency range to 70 GHz. Dynamic range and the field environment in which the probe may be calibrated are the ultimate limits for probes in the order of this small size. The capability of developing broadband probes at NIST is outstanding. Application of these probes to emission measurements as required in the existing standards will yield more accurate results.

g. Electrostatic Discharges

Components and subsystems in many complicated systems perform their command and control functions by computers. Since these computers use low-power semiconductor chips and other sensitive electronics, they are susceptible to electrostatic discharges (ESD) created by contacts and friction between two materials of different triboelectric ranks. While problems due to ESDs by direct contact have been partially eliminated through grounding and bonding techniques, the effects of indirect ESDs (radiation of electric and magnetic fields through air discharges) have only been noted recently [25,26]. Since the rise time of a discharged current waveform can be very fast, in the order of fractions of a nanosecond or smaller, depending on the actual environment and discharging voltage, this current waveform contains a very broad spectrum and radiates fields of significant strengths. For example, the radiated electric field at a short distance away from the ESD source can be as high as a few hundred volts per meter or higher. Although these fields are transient (occurring in a brief duration), they can cause temporary upsets, malfunctions, or other adverse EMI effects on the highly sensitive electronics involved. For this reason, ESD tests are required in the SAE standard for automobiles and aircraft. A direct-contact test by a commercially available ESD simulator was specifically recommended in SAE Method J1113. It requires, however, a clean metal surface of EUT for the ESD simulator to be effective. Discharging to a painted or coated surface often produces unpredictable results. Also, this direct-contact method cannot be used on hard-to-reach areas. For these

reasons, one automobile company has decided in favor of the fixed gap air-discharge method for its validation testing of components [27]. This practice is likely to be included in the future revised SAE standard. However, a caution should be noted. Since the ESD-radiated fields are broadband, wideband equipment will be required for measuring such signals with any physical meaning. Measurements with inexpensive narrowband equipment will not represent the true waveform and may result in errors. NIST has made an initial contribution in this area of measuring simultaneously the fast-rise current waveforms and radiated transient electric fields due to ESDs [25,26]. Its recommendations have been included in "Guide on Electrostatic Discharge from Personnel and Small Mobile Furnishings," issued by IEEE Surge Protective Devices Committee (SPD Working Group 3.6.8).

A new ESD standard is being developed in Europe and may have significant impacts on future U. S. exports of electronic devices and computers to Europe.

h. Bulk Current Injection

A number of radiated susceptibility tests in existing standards, especially that for aircraft equipment, require generation of high electric fields at various frequencies in the open environment. This method may not be practical because it conflicts with the FCC's compliance rule. Consequently, many investigators have suggested that the current-injection method be used to replace it [28, 29], with the hope that this method may be established as an alternative and equivalent evaluation. This method involves injecting currents directly into one or more wires within a bundle. These current magnitudes can be substantial in the actual susceptibility test. It would otherwise require very high radiated fields to induce the same magnitude of currents on those particular wires. Indeed, if it were proven equivalent to the conventional radiated susceptibility test, it would be very advantageous because it can be performed in a laboratory environment, and the injection current can be made as high as the application problem at hand demands. However, preliminary measurement results from a recent study at NIST indicate otherwise [30]. Calculations based on a related theoretical study of this topic at NIST also show significant difference [31]: current distributions on the individual wires in a wire bundle excited by injection are not the same as those excited by radiation. In fact, the difference in test results by the two methods for the same wires (in number and lengths) can be substantial, ±30 dB or more. The difference in result is small only when electrically short wires are involved. However, this may not be the case in practice. Furthermore, the system under test may be nonlinear. Higher current injection does not always produce proportionally more interference. Therefore, current injection has not been able, in general, to yield repeatable measurement data. At a minimum, a serious study of this topic to provide a more meaningful engineering interpretation of the measurement data is desired before it is considered as a standard. Good research results from a study at NIST will benefit the aerospace and EMP-related industry.

4. Conclusions and Suggestions

A review of many EMC-related U. S. standards, either being enforced by government agencies or recommended by voluntary organizations, has been presented. The highlights and unique features for each standard under

review have been outlined and commented on. Deficiencies and potential problems associated with some of these standards have been pointed out from technical considerations. Alternative but better measurement techniques, whenever available, have been suggested. Existing measurement capabilities at NIST are generally adequate to meet the current industrial need. Eight areas -- characterization of EM environment for frequencies above 1 GHz, experimental verification of loop-antenna method for low-frequency testing of radiated magnetic fields with a known EUT, extending application of reverberating chamber to susceptibility testing at much lower frequencies, establishing a standard open-field site for intercomparison, calibration of dipole antennas in a near-field environment, more accurate current distribution on dipoles and mutual-coupling effect, determination of the shielding properties of materials based on near-field simulation and that of containers and gaskets, and validity of the current-injection method being considered in the aircraft industry as an alternative method for EMC tests -- are specifically mentioned as possible future study topics. Since many recent electronic products involve digital systems, more attention should also be paid to the establishment of time-domain measurement methods and facilities with broadband applications to pulsed EMI problems. In addition, while accurate measurements of emissions and immunity of small devices or subsystems are important, those for large products and systems such as vehicles and aircraft, especially when the required testing field is very high, should also be under our consideration for possible future work.

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Important current regulations and standards regarding electromagnetic compatibility (EMC) measurements are reviewed. These regulations and standards have been either enforced by U.S. government agencies such as the Federal Communications Commitssion and Department of Defense, or incorporated in voluntary industrial practice. The specific methods and configurations of measurement required in some of these standards are assessed from a technical basis to see whether or not they are adequate and appropriate. Technical deficiencicies and potential problems, if any, are pointed out together with recommendations of alternative and better methods of measurements. Concurrently, the EMC measurement capability at the National Institute of Standards and Technology is evaluated and appraised for the purpose of planning new metrology activities or programs responsive to the needs of U.S. industry.

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